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program

PROGRAM

Sunday, May 17

15 h 00	OPENING SESSION Moffatt K. (IUTAM representative)
15 h 15	Large scale (vertical) vorticity generation by 3D bores in shallow water Peregrine D.H.
16 h 15	3D bubble plumes behind breaking waves inside surf zone Su M.-Y.
16 h 35	3D patterns in wave generated nearshore circulation Svendsen I.
16 h 55	BREAK
17 h 25	Experimental investigation of the turbulent wake generated beneath a 3D breaker Nepf H.
17 h 45	Normal forms for free surfaces and interfaces Craig W.
18 h 05	Geometrical aspects of three-dimensional ocean patterns Bridges T.

Monday, May 18

08 h 40	Statistical theory of surface waves on shallow water Zakharov V.
09 h 40	The interactions of swell, waves and sea surface roughness Perrie W.
10 h 00	BREAK
10 h 30	Closures for dispersive random waves Tabak E.
10 h 50	Observations on waveforms of capillary and gravity-capillary waves Zhang X.
11 h 10	Spectral characteristics of short wind waves Klinke J. and Jähne B.
11 h 30	Numerical simulation of capillary waves Pushkarev A.
11 h 50	On the interaction among wind, wind waves and swell Mitsuyasu H.
12 h 10	LUNCH BREAK
14 h 30	Spatial variability of the ocean wind stress and sea surface roughness during strong wind forcing Banner M.
15 h 30	Short-crested waves : a theoretical and experimental investigation Kimmoun O., Branger H. and Kharif C.
15 h 50	Numerical simulation of 3D wind-wave interactions Chalikov D.
16 h 10	BREAK
16 h 40	Solution of the initial value problem for the Kadomtsev-Petviashvili equation with quasiperiodic initial data Segur H.
17 h 00	Stability of Kadomtsev-Petviashvili solitary waves de Bouard A. and Saut J.-C.
17 h 20	Nonlinear evolution of a step initial condition in the Benjamin-Ono equation Matsuno Y.
17 h 40	Breaking waves, local singularities and droplet statistics Lathrop D.

Tuesday, May 19

08 h 40 Three-dimensional instabilities of waves and shearing currents
Longuet-Higgins M.S.

09 h 40 3D dynamics of nonlinear water waves on moderately weak shear currents: wave groups and Langmuir's circulations
Shrira V.

10 h 00 BREAK

10 h 30 The initial generation of wind waves and Langmuir circulations
Melville K. and Véron F.

10 h 50 Evolution of oblique solitary waves in supercritical flow
Chen X.-N.

11 h 10 Three-wave quasi-kinetic approximation for nonlinear gravity waves in water of small depth
Zaslavskii M. and Polnikov V.

11 h 30 Three-dimensional wave-wave interactions in both shallow and deep water
Lin R.-Q.

11 h 50 Alternatives to the Kadomtsev-Petviashvili equation for surface water waves
Bona J.

12 h 10 LUNCH BREAK

14 h 30 Qualitative behaviors of wave patterns in simple models
Coullet P.

15 h 30 A lab toy model of air-sea interaction (surface and internal waves)
Wierschem A. and Velarde M.

15 h 50 The influence of rotation on surface and internal solitary waves
Grimshaw R. and Ostrovsky L.

16 h 10 BREAK

16 h 40 Wave interactions in the equatorial waveguide
Milewski P.

17 h 00 3D finite-amplitude internal waves
Akylas T.

17 h 20 Laboratory evidence of frequency downshift in 3D waves in a wave tank
Trulsen K. and Stansberg C.

17 h 40 Spatial variation of atmospheric fluxes and microwave backscatter over the ocean
Plant W.

19 h 30 **BANQUET AT WESTMINSTER HOTEL**

Wednesday, May 20

09 h 00	Wave generation by wind: a comparative study of the effect of randomness and directionality Donelan M.
10 h 00	Wind effects on capillary-gravity waves in the presence of a thin thermocline Das K.
10 h 20	BREAK
10 h 50	On the transition from 2D to 3D water waves Hărăguş-Courcelle M. and Dias F.
11 h 10	A Fourier method for nonperiodic wave interaction Agnon Y.
11 h 30	Capillary ripples on 3D deep-water surface gravity–capillary waves Badulin S. and Shrira V.
11 h 50	The suppression of short waves by a train of long waves Balk A.
12 h 10	LUNCH BREAK
14 h 30	Tranquility or chaos at Venice inlet? Mei C.C.
15 h 30	Three-dimensional evolution of the wind-amplified waves from capillary-gravity to gravity range Caulliez G. and Collard F.
15 h 50	3D wavenumber-frequency spectrum of wind waves Hara T.
16 h 10	BREAK
16 h 40	On the role of nonlinear energy transfer in the evolution of wind wave spectra Masuda A. and Komatsu K.
17 h 00	Detection of nonlinear energy transfer between ocean waves by direct numerical simulations Tanaka M.
17 h 20	3D effects in wind-wave coupling Belcher S.
17 h 40	Wind stress and wave directions: an experimental study Rémy F. and Giovanangeli J.-P.

Thursday, May 21

08 h 40 Simulations of finite Reynolds number free surfaces and interfaces
Zaleski S.

09 h 40 Gravity and capillary-gravity waves for two superposed fluid layers, one being of infinite depth
Iooss G. and Dias F.

10 h 00 BREAK

10 h 30 Nonlinear interaction of inhomogeneous wave-fields on deep water
Rasmussen and Stiassnie M.

10 h 50 Sporadic wind wave horse-shoe patterns on water surface
Annenkov S. and Shrira V.

11 h 10 Orthogonal expansions and normal forms for water waves
Pierce R.

11 h 30 Transition to traveling waves from standing waves
Feng Z.

11 h 50 Limiting configurations of 2D and 3D free-surface flows
Vanden-Broeck J.-M.

12 h 10 LUNCH BREAK

14 h 00 On the Benney-Roskes system
Saut J.-C.

14 h 20 Benjamin-Feir instability of 3D gravity-capillary waves
Il'ichev A.

14 h 40 Numerical simulation of wave breaking in waters of finite depth by using a VOF method
Guignard S., Marcer, Rey V. and Kharif C.

15 h 00 Three-dimensional surface waves propagating over long internal waves
Stocker J.

15 h 20 Flexural gravity waves: stability, resonance generation, edge phenomena
Marchenko A.

15 h 40 CLOSING

abstracts

plenary talks

Spatial variability of the ocean wind stress and sea surface roughness during strong wind forcing

Michael L. Banner
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The wind stress quantifies the complex dynamical coupling between the atmospheric wind field and the sea surface. Because of its central role in air-sea interaction, it has been studied intensively over the past few decades. However, there is significant variation among observations of the corresponding drag coefficient dependence on wind speed reported by different investigators. One potential source of this variability is the influence of the degree of development of the sea state, due to the underlying role of wave form drag in the wind stress. Such a dependence has long been anticipated but has not been easily resolved in the measurements: some recent observational studies have detected a wave age dependence, while this is masked in others. Thus considerable effort continues towards determining and parameterising the sea state dependence in the wind stress, and this remains an important contemporary issue.

Other spatial and temporal sources of variability are also under increasing scrutiny as spatially extensive observations become more readily available through various technological developments, particularly satellite borne instruments. As an illustration, an ERS-1 SAR image taken during quasi-steady strong winds of 17m/s from the south west over the Bass Strait area adjacent to the Southern Ocean reveals longitudinal striations with large streamwise coherence of O(100km) in the wind direction and lateral spacing of O(1-10km). These surface signatures reflect the variability in the short wind wave energy density at the resonant Bragg wavenumber, in this case wind wavelets with O(5cm) wavelengths, and highlights systematic roughness modulations transverse to the wind direction. As inferred from previous studies, they appear to be surface signatures of atmospheric roll cell structures, as shown schematically in the sketch below. Their common occurrence particularly in unstable conditions, can be a significant source of variability in wind stress determinations from fixed platforms. With the indirect methods inherent in such remotely sensed data, more direct measurements are needed to provide further insight into the wind stress and its relationship to the wind speed and sea surface roughness.

The question of wind stress variability is dependent on what space and time scales are used to average the turbulent stress co-spectrum in the marine boundary layer just above the sea surface. This appears to be more complex than might have been anticipated and forms the underlying theme of this paper. In this context, the Southern Ocean Waves Experiment (SOWEX) was an international collaborative (UNSW-NASA-CSIRO) aircraft-based air-sea interaction measurement program conducted in

1992 over the Southern Ocean to investigate the coupled variability in the wind speed, wind stress and sea surface roughness over spatial scales of O(80km), particularly for strong wind forcing conditions. In SOWEX we deployed the NASA Scanning Radar Altimeter aboard the CSIRO F27 meteorological research aircraft. The unique capabilities of the SRA allowed us to observe both wave elevation and mean square slope (mss) as measures of sea surface roughness. During this experiment, we were able to observe both upwind/downwind and crosswind variations over spatial scales of O(80km). [Note: a 20 minute wind stress average measured from a fixed platform, generally considered sufficient to close the stress co-spectrum, corresponds to an advection of 12km for a 10m/s wind speed].

The SOWEX observations were made in the marine surface boundary layer at a minimum elevation consistent with safety requirements in the wide range of wind conditions that prevailed. Amongst the major findings of this study to be described in detail at the symposium are:

- the wind field was dominated by atmospheric roll cells, even during gale force wind conditions. These cells have a spectrum of wavelengths that increases from O(1km). Their associated velocity field has strong low wavenumber signatures in which updraught regions are systematically associated with reductions in the mean wind speed. These regions contribute significantly to the downward momentum flux.

- a remarkably high coherence was found between the mean wind speed variations and corresponding sea surface mss variations averaged over 1.9 km (the minimum averaging for stable mss estimates from the SRA data). The comparably averaged vertical momentum flux observed at heights from 30m - 90m showed much less coherence with the variations in wind speed and mss. However, the wind stress requires a much longer averaging distance [O(10-20km)] and cannot be compared in this way.

- on one of the strongest wind speed days, we observed a large crosswind variation in the 10 km and 20 km averaged wind stress. This appears to be consistent with coherent structures in the planetary boundary layer which have a horizontal/vertical aspect ratio of O(10).

The SOWEX data has provided new insight into three-dimensional aspects of the variability underlying the wind stress, at the same time raising fundamental questions concerning the vertical structure of the flow in the surface boundary layer and the response of the sea surface to variations in wind forcing. These will be described in the presentation.

WAVE GENERATION BY WIND: A COMPARATIVE STUDY OF THE EFFECTS OF RANDOMNESS AND DIRECTIONALITY

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The generation of waves by wind is central to many, perhaps most, air-sea interaction problems. Although there have been significant advances in both theoretical and experimental treatments of the problem, a full understanding of the mechanisms and their efficiencies is lacking. The flow of air over a wavy surface is highly turbulent and may separate intermittently from the surface leading to large local fluctuations in the rate of momentum and energy input into the waves. The waves themselves are often treated both theoretically and experimentally as narrow banded, if not monochromatic, as this greatly eases the difficulty of finding an analytic or numerical solution and allows the experimenter the convenience of assuming that the paddle-introduced sinusoid is decoupled from the relatively broad-banded wind-generated spectrum in the tank.

Real wind-generated seas vary locally in height, steepness and direction, and insofar as these may alter the mechanisms of wave generation by wind, it behoves us to explore their effects. In this paper I report on measurements in a large wind-wave tank of the pressure on the surface of waves and consequently the principal source of their generation. The tank's dimensions are 100 m x 4.57 m x 3.06 m (L x W x H) and it contained water to a depth of 1.2 m. The width of the tank was sufficient to support a fairly wide directional spectrum of wind waves – albeit narrower than typical wind seas on open water bodies – and use was made of this to explore the effect of propagation at substantial angles to the wind on the rate of generation of wind waves. A pair of capacitance wave staffs, aligned across the tank and 10 cm to either side of the pressure probe, served the dual purpose of measuring the wave height at the pressure probe and the direction of approach of each wave. The pressure probe was mounted on a wave-follower that was capable of flat response to about 3 Hz and so maintained the probe within a few millimeters of a pre-determined height above the surface. In order to assess the likelihood of flow separation, an optical 'white-cap' sensor was installed in the ceiling of the tank and received light from an area of the surface about 400 cm^2 in extent and about 20 cm upwind of the pressure probe. The surface was illuminated by a lamp placed laterally and beamed at 45° to the surface, so that when the surface was broken by spilling breakers the optical sensor registered a substantial increase in the light level. The intensity of the response was used as an indicator of intensity of white-capping, while the duration yielded the extent of the breaking patch. The recordings from the pressure transducer, the capacitance wave staffs and the white-cap sensor were analyzed using Morlet wavelets. Experiments were performed with paddle-generated sinusoids or spectra matched to parametric descriptions of oceanic spectra

in which the phases of the component waves are random. The wind was varied in 4 steps: approximately 0, 3.3, 6.6 and 9.9 m/s and the amplitude of the paddle waves was also stepped from run to run.

The following comparative studies were performed:

a) the effect of wave breaking on altering the rate of energy input to waves near the peak of the spectrum was explored. While wave breaking did produce an enhancement of the input, and there was a continuous favourable (for generation) shift of the pressure phase with respect to the wave for a wide range of breaking intensities, with intense breaking the amplitude of the induced pressure was reduced thereby producing a 'saturation' of the growth rates.

b) the change in wind input to waves propagating off the wind direction. Significant energy was recorded at angles as large as 35° for pure wind seas in the tank. The growth rates were first sorted by the degree of white-capping and then, within these groups, further sorted by the angular deviation from the axis of the tank. The generation rate fell off quickly with off-wind angle.

THREE-DIMENSIONAL INSTABILITIES OF WAVES AND SHEARING CURRENTS

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In recent laboratory experiments on the initial stages of wave growth under the action of a steady wind, Melville et al. (1998) have observed the presence of 3D streamwise vortices, before and simultaneously with the generation of waves travelling in the direction of the wind. The initial flow is laminar. To explain these phenomena a hydrodynamical theory is required in which the surface current is assumed to be of the same order of magnitude as the phase speed of the waves, and in which the viscosity of the fluid is taken into account.

The present paper represents an attempt to construct such a theory, starting with the initial instability problem and following the development of the perturbation to finite amplitudes. The nonlinear interaction between the waves and the surface current is significant and is calculated on certain simplifying assumptions.

NOTES

Tranquility or chaos at Venice inlet?

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For reducing the hazards of flooding in Venice, storm barriers have been designed to span the three inlets of Venice Lagoon. The proposed barriers will consist of a series of hollow steel gates which are unconnected to each other but hinged at the bottom along a common axis on the seabed. In calm weather the gates rest horizontally on the seabed so as not to obstruct normal navigation or to impair the scenic view of the area. In stormy weather, all gates will be raised by buoyancy to an inclination of about 50° from the horizontal, and hence will act as a dam. The gates are otherwise free and are expected to swing to and fro in unison in normally incident waves and maintain the sea-level difference. Laboratory experiments with sinusoidal waves incident normally on two or three gates in a narrow flume, or on a large number of gates in a wide basin, have however revealed that neighboring gates may oscillate out of phase in a variety of ways, at half of the frequency and with relatively large amplitude. The out-of-phase motion must be understood in order to take proper measures for preserving the intended efficiency of the gates as a dam.

It is known that edge waves which are natural modes trapped on a sloping beach can be resonated subharmonically by incident waves. Mei *et al.* (1994) showed that articulated gates of finite dimensions hinged at the bottom can also support trapped waves even if they are upright in the state of static equilibrium. They deduced a linearized theory for the eigenmodes, and performed confirming experiments. Furthermore they have given experimental evidence that the gate resonance is indeed associated with these trapped modes and anticipated that the nonlinear dynamics should also be governed by the Stuart-Landau equation.

In this talk, we describe a weakly nonlinear theory of the mobile-gate dynamics, by both theory and experiment, for a series of hinged gates which are vertical at static equilibrium (Sammarco et al, 1997a). We first derive the anticipated evolution equation. The dependence of all coupling coefficients on the gate characteristics will be examined. The effects of steady incident waves will then be studied. Laboratory experiments are performed to compare with theoretical predictions. For best corroboration between theory and experiment two viscous damping terms are found to be necessary, one linear for lower amplitudes and one quadratic for higher amplitudes. The coefficients of these damping terms are determined empirically from free oscillation tests without incident waves. With incident waves the predicted hysteresis and jump phenomenon are verified.

In order to examine the effects of finite bandwidth of the incident sea spectrum, we

consider a narrow band consisting of the carrier frequency and two sidebands (Sammarco et al, 1997b). The evolution equation for the gate oscillations now has a time-periodic coefficient, and is equivalent to a non-autonomous dynamical system. For small damping and weak forcing, approximate analysis for local and global bifurcations are carried out, and extended by direct numerical simulation. Typical bifurcation scenarios are also examined by laboratory experiments.

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Large scale (vertical) vorticity generation by 3D bores in shallow water

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Explicit expressions for the vorticity generated by incident waves breaking in the surf zone are presented. They give powerful new insight into the generation of surf zone currents.

1. Introduction

Ordinarily, whether considering theory or data interpretation, we consider the sea surface to be smooth with irrotational water waves for which we can perform all sorts of analysis. However, whenever there is any significant wind blowing there is wave breaking, perhaps only micro-breakers but often intermittent white caps. Each and every such breaker transfers momentum from wave motion to currents and in doing so generates some larger scale vorticity. This vorticity is distinct form the smaller scale vorticity which is the signature of the turbulence generated by breaking. Study of the flow generated by breaking in deep water has commenced, e.g. in the work of Rapp & Melville (1990), but this is restricted to two-dimensional mean flows, whereas in deep water most breakers are fully three-dimensional. However, in shallow water waves break and continue breaking as bores for which there is a simple and tested model. That is bores can be represented within the shallow water wave equations as discontinuities in the surface and flow field that conserve mass and momentum, while energy is dissipated.

2. Circulation

The inviscid nonlinear shallow water equations are such that Kelvin's circulation theorem holds for smooth continuous solutions. That is the circulation around a material circuit is constant. However, the theorem is not valid for solutions with discontinuities such as our representation of bores. The rate of change of circulation around a material circuit cutting one or more bores has been derived. The result is suprisingly simple. The rate of change is directly proportional to the sum of the rate of dissipation of energy at each of the points where the material circuit cuts a bore, with each such point being assigned a sign depending on the direction in which it is being cut. Thus an infinitely long bore of constant height on constant water depth generates no vorticity since any material circuit cuts it twice in opposite directions. On the other hand if there is an end to this bore and a material circuit goes around the end of the bore there is a single contribution giving net production of circulation. Thus anywhere where you can see the end of a breaker circulation is being developed.

3. Vorticity

The generation of vorticity at a bore is a little more complicated, since it falls into two parts. Consideration of a small rectangular material circuit as it passes through a bore gives a contribution corresponding to the gradient in dissipation along a bore. This term gives the response to gradients in both bore height and water depth along the bore. For example, obliquely incident waves on a sloping beach lead to bores generating the vorticity which corresponds to the shear across a longshore current.

The second contribution to vorticity generation at a bore comes from the change in water depth across the bore. For a uniform bore the column of water circumscribed by the material circuit increases in height as it passes through the bore. Thus although the circulation is constant the vorticity within the circuit is increased by the vertical stretching. This represents conservation of potential vorticity. The same mechanism is at work when an eddy propagates into deeper water, as can be seen by considering a material circuit enclosing its vorticity. Thus, as an eddy is stretched it has the same circulation at a smaller radius, and although the strength of the vorticity increases the influence of the eddy on the rest of the flow diminishes. The above results are presented in Peregrine (1998).

4. Interpretation of flows

By simple consideration of these results much of the way in which a given irregular wave pattern is contributing to the generation of currents may be seen by visual inspection of the bores.

i. Any bore which has a 'free' end is generating vorticity. This vorticity may roll up into a vortex, if there is no nearby vorticity giving other interactions. On the other hand if there is another free end nearby they may jointly provide the shear layers alongside a current jet such as a rip current, or, perhaps just as likely, form a couple of vortices that can move offshore under their mutual influence.

ii. Where one bore is obliquely overtaking and merging with another, there is a strong gradient in bore properties leading to a trailing strip of vorticity which corresponds to the slip line that occurs in gas dynamics when oblique shock waves meet. In the water-wave case there is also a weak trailing surface wave.

iii. Often bores cross bed slopes obliquely. The resulting shear flows can be envisaged relatively simply, by using the straight beach as a guiding example. This contrasts with the usual approach to the generation of longshore currents which relies on the conservation of momentum from consideration of the appropriate component of the radiation stress tensor.

5. Conclusion

From the point measurements that are usually obtained in field experiments it is hard to obtain an overall view of the surf zone currents, and the currents are difficult to observe in other ways because of the dominating influence of the incident waves. The quantitative results that have been obtained for the changes in circulation and vorticity due to non uniform bores can add to our picture of these currents from observation of the bores and help to evaluate their relevance for sediment transport. Detailed computations are planned to improve understanding further, since there are difficulties of interpretation where the currents have a strong feedback onto the incident waves, and also where the bed topography is not known.

On deep water we can see that a similar circulation is developed for material circuits residing on the water surface. However, the vortex lines for the resulting flow will initially join beneath the breaking region, and the evolution of three-dimensional vortex fields is more difficult to follow than the almost two-dimensional shallow water example. However, some of the ideas may prove illuminating for the deep water case.

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NOTES

Statistical Theory of Surface Waves on Shallow Water

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Waves on shallow water are charactarized by two parameters, $\mu = (ka)^2$ and $\delta = kh \ll 1$. Here k, a are wave number and amplitude, h is depth. Self-consistent weakly nonlinear theory can be developed if

$$\mu \ll \delta^5 \tag{1}$$

Outside of a narrow near-coastal zone $\delta \geq 0.3$, and condition (1) is moderate.

The main process in the weakly-nonlinear theory is a four-wave interaction, described by a standart kinetic equation

$$\frac{\partial h}{\partial t} + \frac{\partial \omega}{\partial \vec{k}}\frac{\partial h}{\partial \vec{r}} - \frac{\partial \omega}{\partial \vec{r}}\frac{\partial h}{\partial \vec{k}} = st(n,n,n) \tag{2}$$

$$\begin{aligned} st(n,n,n) &= 4\pi \int |T(k,k_1,k_2,k_3|^2 \delta(k+k_1-k_2-k_3)\delta(\omega_k+\omega_{k_1}-\omega_{k_2}-\omega_{k_3}) \times \\ &\times (n_{k_1}n_{k_2}n_{k_3} + n_k n_{k_2} n_{k_3} - n_k n_{k_1} n_{k_2} - n_k n_{k_1} n_{k_3}) dk_1 dk_2 dk_3 \end{aligned} \tag{3}$$

Here $\omega_k = \sqrt{gh \tanh kh}$ is a dispersion relation, and n_k is a "renormalized" wave action. The energy spectrum is expressed through n_k by infinite asymptotic series

$$\epsilon_k = \omega_k \{n_k + n_k^{(1)} + \cdots\} \tag{4}$$

Higher terms in (4) are small only if condition (1) is satisfied. Difference between n_k and ϵ_k/ω_k is very important for comparision of the theory and the experimental data.

The interaction coefficient $T_{kk_1k_2k_3}$ consists of terms of order $k^3/(\tanh kh)^3$. But at $\delta \to 0$ the major terms of order $1/h^3$ on the resonant surface are exactly cancelled. This is a nontrivial fact, and can be explained in a following way. At $\delta \to 0$ the surface waves are described by the Kadomsev-Petviashwili equation, KP-2, which is a completely integrable system. In spite of this cancellation, the four-wave interaction on a shallow water is stronger than on a deep water by a factor $(\tanh kh)^{-4}$.

The stationary kinetic equation, $st(n,n,n) = 0$, has Kolmogorov-type solutions

$$n_k^{(1)} \simeq P^{1/3} k^{-10/3}$$

$$n_k^{(2)} \simeq Q^{1/3} k^{-3}$$

Here P is flax of energy at large k, and Q is flax of wave action to small k.

For a very shallow shallow water, $\mu \geq \delta^5$, the weakly nonlinear theory fails, and one has to develop a theory of solitonic turbulence.

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NOTES

Simulations of finite Reynolds number free surfaces and interfaces

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I will discuss numerical methods for the simulation of flows with interfaces and free surfaces. When interfaces undergo large deformations, as in instability or wave problems, it is efficient to track the interface on the fixed grid used to solve the momentum-balance equation. Volume-tracking methods, such as the VOF method, have enjoyed vast popularity. This is due to their ease of programming, the easy generalization from two to three dimensions and the natural conservation of mass. Another benefit is the automatic topology change that occurs in certain cases of breakup or coalescence.

Another type of fixed grid method follows the interfaces as splines connecting tracer points or markers. These methods are often more accurate for the calculation of surface tension forces. I shall describe several implementations of surface tensions and tests of the accuracy. Applications to spray formation and breaking waves will be shown.

NOTES

contributed talks

A Fourier method for nonperiodic wave interaction

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Spectral methods are very powerful for solving problems which involve the propagation of waves. They are ideally suited to periodic problems in homogeneous media and have often been applied to such problems. A new method is developed which allows the spectral method to be successfully applied to nonperiodic problems in inhomogeneous media. The method utilizes the FFT algorithm to obtain efficient and accurate solutions. The evolution of a wave field is used as a model problem to demonstrate the method.

Fourier functions have several properties which make them attractive for application to 3D wave problems. The functions and their derivatives are easy to compute, they are nonsingular, a small number of functions yields high resolution (typically almost exponential convergence), and their coefficients can be efficiently computed via the fast Fourier transform (FFT). Their disadvantages are that the functions are spatially periodic, and the medium is assumed to be homogeneous (of constant depth). In the present work we overcome these disadvantages in the following way. The boundary value problem is decomposed into a sum of two problems, a simple "steady flow" type solution which allows open or radiation conditions to be satisfied at the lateral control surfaces, and a periodic (in space) potential which ensures satisfaction of the free surface and body boundary conditions. In this way the accuracy of a spectral representation can be enjoyed for non-homogeneous and spatially non-periodic problems. The method can be fully nonlinear, or weakly nonlinear waves can be assumed throughout a large part of the domain to reduce the computational cost. Ideally, only a rather small part of the computational domain around the wave generation area is treated in a fully nonlinear way, so that the overall computational effort is relatively small. In the present work we assume that the bottom is flat and focus on the wave evolution. We have also extended the method to the case of variable depth. This will be reported separately.

NOTES

THREE-DIMENSIONAL FINITE-AMPLITUDE INTERNAL WAVES

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A theory is developed for the propagation of weakly three-dimensional long internal waves in a uniformly stratified Boussinesq fluid. The flow is shown to be governed by an integral-differential equation which is capable of describing finite-amplitude disturbances and is valid until incipient density inversions take place. In addition to the nonlinearity caused by the presence of flow transience, it is found that three-dimensional effects are also manifested as nonlinear terms in this evolution equation which, as expected, reduces to the familiar KP equation in the small-amplitude limit. Based on this theory, the stability of large-amplitude solitary internal waves to transverse perturbations is then examined. It is shown that the stability criterion that applies to KdV solitary waves holds for large-amplitude solitary waves as well.

NOTES

Sporadic wind wave horse-shoe patterns

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The work considers three-dimensional crescent-shaped ('horse-shoe') patterns often seen on water surface in natural basins and observed in wave tank experiments. The most common patterns appear to be sporadic, emerging spontaneously under varying conditions, and are characterized by their crescent-shaped form with the convex side always oriented downwind. This paper suggests a qualitative model of these structures aimed at explaining their sporadic nature, physical mechanisms of their selection and their specific asymmetric form.

First, the phenomenon of sporadic horse-shoe patterns is studied numerically using the novel algorithm of water waves simulation recently developed by the authors. The numerical simulation shows that a steep gravity wave subjected to small dissipation and embedded into primordial noise of wide spectrum typically follows the simple evolution scenario: most of the time the system can be considered as consisting of just a basic wave and a pair of symmetric oblique satellites, the choice of the specific pair being in general case different at different instants. The system may also contain Benjamin-Feir satellites but they appear to be of no qualitative importance for longtime dynamics. Despite the fact that the dynamics of multimodal system is effectively low-dimensional at relatively short time spans, small satellites play an important role. In particular, in their presence the developed satellites exhibit more pronounced maxima.

The explanation of the observed phenomena is based on the consideration of interactions between different oblique satellites lying in the domain of the five-wave (McLean's class II) instability of the basic wave. It is demonstrated that small satellites can affect the system dynamics via the quartic resonant interactions at the same timescale as the quintet interaction with the basic wave. These interactions give rise to a specific selection mechanism: the satellites tend to push each other out of the resonance zone due to the frequency shifts caused by quartic interactions, so that each pair of growing satellites inhibits the growth of other pairs, and, as the class II instability domain is narrow (of order of cube of the basic wave steepness), eventualy only a single pair survives in generic situation. The interplay of quartic and quintet interactions and nonconservative effects are shown to be responsible for the specific fronts asymmetry.

NOTES

CAPILLARY RIPPLES ON THREE-DIMENSIONAL DEEP WATER SURFACE GRAVITY-CAPILLARY WAVES

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The work is concerned with physical mechanisms of capillary ripples (with wavelengths less 1 cm) on the crests of gravity-capillary water waves (wavelengths $5 - 10$ cm). It develops further the idea that a specific nonlinearity/dissipation balance established by previous studies (Longuet-Higgins 1995; Ruvinsky & Freidman 1981) is the key for this phenomenon. The study is aimed at explanation for the experimentally observed existence of capillary ripples at relatively low steepnesses ($ak \approx 0.05 - 0.1$) of longer gravity-capillary waves.

There are two principal new elements in the study:

- three-dimensional water waves are considered;
- modulation of the thin boundary layer by gravity-capillary waves just beneath the surface is specified within the three-dimensional problem (in the spirit of approach by Banner & Phillips 1976).

Parameters of capillary ripples affected by long wave modulated boundary layer are found by means of WKB technique. Some aspects of the problem are also considered within the weakly-nonlinear problem of phase-group resonance of capillary wave packet and long gravity wave.

It is shown that in the three-dimensional case physical mechanism proposed by Longuet-Higgins (1995) is more effective. Short wave blocking ("supercritical regime" in terms of Longuet-Higgins) and associated strong ripple localization become possible at considerably lower long wave amplitudes. Spots of stronger dissipation of ripples resulting in thickening of boundary layer can be both at forward and rear slopes of long wave depending on three-dimensional structure of the latter.

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NOTES

THE SUPPRESSION OF SHORT WAVES BY A TRAIN OF LONG WAVES

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It has been noticed in several experiments during the last 30 years (Mitsuyasu 1966; Banner 1973; Phillips & Banner 1974; Yuen 1988) that a long wave can suppress short waves: the energy density of a short-wave field can decrease when a train of longer waves propagates into the short-wave field.

This surprising phenomenon was observed in laboratory experiments with wind-generated water waves. Although its physical mechanism was not entirely understood, it was connected to the drift current (under the water surface) induced by the wind.

The aim of this talk is to show that a train of long waves can suppress short waves merely due to the 4-wave resonance interactions of small amplitude waves, so that the presence of the drift current is not required, and the phenomenon can occur in continuous media of various physical nature.

The interaction between the long wave train and the short wave field leads to the diffusion of the latter in the Fourier space, so that the wave action of the short wave field is transported to the regions of higher wave numbers, where the short waves dissipate more effectively. The diffusion equation is derived.

NOTES

THREE-DIMENSIONAL EFFECTS IN WIND–WAVE COUPLING

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Recent work has shown that growth and decay of ocean waves is controlled by both the sheltering in the lee of the wave induced by turbulent stresses in the air flow (Jeffreys 1925; Belcher & Hunt 1993), and also by dynamical effects of the critical height (Miles 1957). The relative importance of these mechanisms changes across the range of wind and wave speeds, c/u_* (c is the wave phase speed and u_* is the friction velocity of the air flow).

Extension of these ideas to air flow over three-dimensional waves is just begining and may well provide a good way of discriminating between current theories. For linear analysis of waves of low slope, the canonical problem is wind over waves that propagate at an angle to the wind, θ. Preliminary studies of sheltering over such waves show that when the waves are strongly forced by the wind the growth rate varies with angle nearly as $\cos^2\theta$, which is what would be naively expected by using the component of the wind speed parallel to the direction of propagation of the waves. These results will be described in the talk and compared with results from the critical layer mechanism obatined by Morland (1996).

NOTES

Alternatives to the Kadomtsev-Petviashvili equation for surface water waves

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The Kadomtsev-Petviashvili (KP) equation was derived as an enhancement of the Korteweg-de Vries theory for unidirectional propagation of long-crested waves, to allow for weak dispersive effects in the direction orthogonal to that of primary propagation. Suitable generalizations of this equation have recently been used in modelling near-shore zone waves and the resulting sediment transport.

One troublesome aspect of the KP equation is that is does not allow for global mass and energy transfer in the cross-shore direction. Especially when coupled with a model for sediment movement, this is a substantial limitation.

We propose here new models for two-dimensional, unidirectional surface-wave propagation that have the same formal accuracy as the KP-equation, but which do allow for weak transfer of mass in the longshore direction. We take a Hamiltonian approach and derive a class of models. Some preliminary analysis on these models will be also be reported.

This work is joint with Hongqiu Chen, Michael Tom and Ron Smith.

NOTES

GEOMETRICAL ASPECTS OF THREE-DIMENSIONAL OCEAN PATTERNS

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The talk will focus on variational principles for three-dimensional patterns on the ocean surface, including the effect of meanflow. In the recent work of Hammack et al [1995], it was found that hexagonal doubly-periodic patterns are robust and basic wave patterns in shallow water and exact solutions of the KP equation were constructed as models for these patterns. In Bridges [1998] it is shown that there is a natural multi-symplectic structure of the KP equation that leads to a constrained variational principle for KP multi-periodic patterns. It is then shown that this same multi-symplectic variational structure extends to the full equations for water waves, suggesting a approach to calculating hexagonal wave patterns of the full equations, including meanflow effects. Some implications of the variational structure for stability will also be discussed. Another shallow-water pattern of great interest is short-crested Stokes waves (SCWs). In recent work of Bridges, Dias & Menasce [1998], a new formulation of this problem is proposed, where SCWs are characterised as steady rectangular multi-periodic patterns on a uni-directional meanflow, and some of the implications of this formulation will be discussed.

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NOTES

3D EVOLUTION OF THE WIND-AMPLIFIED WAVES FROM CAPILLARY-GRAVITY TO GRAVITY RANGE

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To better know the 3D feature of wind wave fields is of prime importance now for progress in our basic understanding of the air-sea interaction processes and for remote sensing applications. However this aspect of the wind wave field evolution has been poorly studied yet as the description provided by classical tools used in most observations, i.e. single-point measurements and spectral analysis, is limited. In this paper, we report on a laboratory study carried out in the large IRPHE-Luminy wave-wind tank to investigate in detail the formation of wind wave 3D patterns in the capillary-gravity and gravity ranges. For this purpose, a two-color visualization technique allowing one to measure simlutaneously the slopes of the waves in two perpendicular directions was used.

This experimental study of wind waves at such relatively short fetches as observed in a 40 meter long tank has revealed the 3D wave patterns as the dominant feature of the wave field in the range of gravity-capillary and short gravity waves, i.e. in the range of wavelengths 2-25 cm. Various types of 3D patterns emerging at different stages of wind wave field evolution were identified. The patterns are deterministic in the sense that each particular type of patterns occurs only within a specific range of parameters such as fetch, wind speed, and corresponds to a particular range of wave scales and wave steepness. The typical features of these patterns were found by means of the classical spectral methods and new methods of data analysis. The wind wave field development is found to be characterized by a gradation of coherent 3D patterns composed of a few basic harmonics and more random 3D patterns. The possible mechanisms of the pattern formation are then discussed.

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NUMERICAL SIMULATION OF 3D WIND-WAVE INTERACTIONS

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A new theoretical approach to investigate the nonlinear wave dynamics and wind-wave interaction is developed based of coupled modeling of wave boundary layer (WBL) and surface waves. The WBL is defined as the lowest part of the atmospheric boundary layer above the ocean surface wave field whose structure is directly influenced by wave-produced fluctuations of velocity and pressure. The exchange of momentum, energy and mass between air and water depends considerably on the specific properties of the WBL. Direct empirical data on the statistical structure of the WBL are sparse, and the only viable method of investigating the WBL is through numerical modeling. The present version of coupled WBL-Waves model is based on the nonstatic Euler equations written in nonstationary surface-following coordinate system in the 3-D domain for water and air layers separated by arbitrary, but two-periodic and single-valued moving surface, which may be represented by 2-D Fourier series. Movement of surface satisfies to kinematic boundary conditions. Euler equations are averaged to obtain the Reynolds equations. The closure scheme is based on the full turbulent energy evolution equation and a turbulent scale growing linearly with a distance from a surface. Statistical effects of subgrid waves are taken into account in formulation the algorithms for momentum and turbulent energy exchanges through an interface. Parameterization of breaking effects is based on local adjustment of surface to critical steepness and tranformation of released potentila energy into energy of tubulence. The numerical scheme for both layers is based on a Fourier representation in the horizontal and a gridded representation in the vertical for each variable. Nonliearities are calculated by transform method. Pressure field is calculated semi-implicitly. The solutions for air and water counterparts are coupled at each time step by matching of surface stresses and velocity components. Shape of the surface is taken into account in both models through metric coefficients. At the upper and lower boundaries, all wave produced perturbations vanish and a value for the vertical flux of horizontal momentum is assigned as a main governing parameter of the joint problem. In principle, it is supposed that model was created for MPP computers type of Cray T3E (with about 1000 processors). Some preliminary results of simulating the coupled dynamics of the WBL and multi-mode waves obtained with Cray C90 (16 processors) are represented. The spectral structure of wave-produced velocity, pressure fluctuations and momentum fluxes are investigated. It is found that flux of energy from wind to waves cannot be represented as a superposition of fluxes to separate modes in the spectrum. The method developed may be applied to a broad range of wave dynamics and wind-wave interaction problems where the assumption of two-periodicity is acceptable. The advantages and restrictions of this approach are also discussed.

NOTES

Evolution of Oblique Solitary Waves in Supercritical Flow

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It is considered that a slender structure sits in a shallow water flow sheet over a homogeneous or periodically varying topography. Specially it is assumed that the incident stream velocity U is supercritical, i.e. larger than the critical value $\sqrt{gh}$ and the topography is very mild and relatively stationary with respect to the structure.

It is well-known that a slender structure can generate oblique solitary waves (Karpman 1975, Mei 1976), if its shape is suitably chosen. Generally this stationary problem can be described by a Boussinesq-type equation or even by a KdV-type equation, in which the transverse coordinate y plays a same role as the time in original equations (Chen & Sharma 1996).

In this paper, I study the evolution of such oblique solitary waves. Two cases are investigated: generation of solitary wave-train by a wedge-shaped strut over an even topography, and evolution of a single oblique soliton over a periodically varying topography. For the first case, Whitham's average method is applied to show that the shock wave jump at the initial position $y = 0$ will develop to a cnoidal wave train, which is exactly same as that of initial value problem of KdV equation studied by Zakharov et al. (1980). For the second case (uneven topography), by means of shallow water wave approximations, a forced KdV equation is derived. The slender structure is so chosen that it generates a single soliton initially. The question is how the soliton evolves further over the uneven topography. The adiabatic perturbation result due to Karpman & Maslov (1978) is applied. Two coupled ordinary differential equations with periodic disturbance are obtained for the soliton amplitude and phase (position). Numerical solutions of these equations show chaotic motion of this perturbed soliton. Some features of this chaos are discussed. One of reduced cases may be related to Kirchgässner's result (1991). He shows by means of Melnikov's integral that if a capillary gravitational solitary wave is disturbed by a stationary periodic pressure, spatial chaotic wave patterns can be formed.

Numerically solutions will be also carried out for both cases in order to confirm the interesting results obtained by the perturbation theories.

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On the transition from two-dimensional to three-dimensional water waves

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The appearance of crosswise modulations of two-dimensional (2D) water waves and herewith of three-dimensional (3D) waves is studied analytically.

There are two main processes giving rise to 3D waves: the dimension-breaking bifurcation through which a 2D wave of finite amplitude bifurcates into a 3D wave and the bifurcation from the rest state. These two processes were described from a mathematical point of view by Hărăgus & Kirchgässner [1995] (*Pitman Research Notes* 335), who considered two model equations to illustrate them: the Ginzburg-Landau equation for the dimension-breaking bifurcation and the Kadomtsev-Petviashvili [1970] equation for the bifurcation from rest. Three-dimensional water waves which have been studied in the literature are essentially of the two main types described above: small-amplitude waves (which bifurcate from the rest state - examples of such waves are the so-called short-crested waves, which result from the superposition of two oblique travelling waves) and large-amplitude waves (which bifurcate from a large-amplitude 2D Stokes wave – see the work of Saffman and his coauthors in the early eighties).

We show that if one considers capillary–gravity waves, one can find parameter regimes where dimension breaking bifurcations can be obtained within the framework of the so-called Benney–Roskes–Davey–Stewartson (BRDS) equations. These (two) equations couple the mean flow with the modulations of the wave train. The dimension-breaking procedure is fully justified when both equations are of elliptic type. Dimension-breaking bifurcations from large-amplitude 2D periodic waves are studied. We obtain crosswise modulations which are either periodic, quasi-periodic, homoclinic, or heteroclinic. In particular, both symmetric and asymmetric waves are constructed. The existence proofs are based on the theory of spatial dynamical systems and on center manifold theory.

NOTES

Normal forms for free surfaces and interfaces

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This talk concerns the water wave problem for a free surface, and the Kelvin-Helmholtz problem for a free interface with zero mean shear flow. The first several Birkhoff normal forms for these problems are calculated, giving information about their phase space and about the initial value problem. In particular we single out the facts that the fourth order normal form for water waves is an integrable system while the analogue fourth order system for the Kelvin-Helmholtz problem is not, and the existence of homoclinic solutions for resonant subsystems of the Kelvin-Helmholtz problem.

NOTES

Wind Effects on Capillary-gravity Waves in the Presence of a Thin Thermocline

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A fourth order nonlinear evolution equation is derived for a capillary-gravity wave packet in deep water in the presence of a thin thermocline including the effect of wind and viscous dissipation in water. In deriving this equation it has been assumed that the wind-induced basic current in water is exponential and the wave-induced disturbances are governed by Navier-Stokes equation. The kinematic boundary condition gets modified by the boundary layer correction. The effect of normal stress due to wind appears in the normal stress boundary condition. The nonlinear evolution equation is used to study the stability of a uniform capillary-gravity wave train. Expressions for the maximum growth rate of instability and wave number at marginal stability are obtained. Graphs are plotted showing the variations of the maximum growth rate of instability against wave-steepness for some different values of dimensionless thermocline depth and air-friction velocity. Similar graphs are drawn for wave number at marginal stability. These graphs help us to examine the effects of wind and thermocline on the stability of a uniform capillary-gravity wave train.

NOTES

Stability of Kadomtsev-Petviashvili solitary waves

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Some properties of Kadomtsev-Petviashvili type localised solitary waves are described, such as existence, symmetries, decay at infinity and stability. These properties are shown to be close to those of the "lumps" solutions of the KPI equation. For example, the decay rate at infinity is at least the same as the decay rate of the lumps, and cannot be much more in many cases. The stability properties are investigated by using variational techniques. The set of ground states is found to be stable under suitable assumptions on the nonlinearity, assumptions which are satisfied of course for the KPI equation. The question of uniqueness of the ground state remains open.

NOTES

Transition to Traveling Waves From Standing Waves

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We report experimental observation of a transition to traveling waves from standing waves. The waves are two dimensional and are generated in a rectangular container excited by a horizontal sinusoidal motion along its length.

Theoretical understanding of the phenomenon is based on the energy tranfer mechanism between two neighboring modes. In general a standing wave of odd mode number whose frequency is close to the forcing frequency is excited. However, we show in this paper that the neighoring even mode, though not directly excited, may be excited through an energy transfer from the odd mode. As a result, the wave response becomes superposition of two standing waves which are not in general in phase with each other. Consequently the mixed-mode wave motion is not standing waves but traveling waves. We employ a perturbation method to derive amplitude equations governing the dynamics of these two modes. Studies of the steady-state solutions and their stability lead to bifurcation diagrams showing the sequences of the events leading to the instability and the parameters for which the standing waves become unstable.

NOTES

THE INFLUENCE OF ROTATION ON SURFACE AND INTERNAL SOLITARY WAVES

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The effects of the Earth's rotation on surface and internal solitary waves is considered within the framework of the rotation-modified Korteweg-de Vries equation. Using an asymptotic procedure, solitary waves are shown to be damped due to the radiation of a dispersive wave train propagating, near the solitary wave, with the same phase velocity. Such a synchronism is possible due to the presence of rotational dispersion. The damping law is found to be "terminal" in that the solitary wave disappears in a finite time. The radiated wave amplitude and the space-time sttucture of the radiated "tail" are found. The asymptotic results are confirmed in numerical simulations.

NOTES

NUMERICAL SIMULATION OF WAVE BREAKING IN WATERS OF FINITE DEPTH BY USING A VOF METHOD

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The investigation of wave induced coastal dynamics is of practical importance in oceanography and in coastal engineering. In the Mediterranean, the main forcing at the origin of beach erosion is the wave breaking.

In the present paper, a numerical simulation of the wave breaking is presented. The 2D Navier-Stokes equations are solved in air and water thanks to a pseudo compressibility method using a finite volume dicretization. The free surface description is based on the fractional volume of fluid concept (VOF). A new high CFL Lagrangian second order method modeling the interface and its evolution is used for the calculation of the VOF field.

The calculation is initialised with a solitary wave propagating on a constant water depth. The characteritics of the initial condition, the interface shape, the values at the interface of the potential and its derivative, are calculated thanks to a Tanaka's algorithm. The initial velocity and pressure fields are then calculated from these values thanks to a BIEM computation.

Studies concerning the wave shoaling and breaking are reported for different sloping beach shapes. Successful comparisons with BIEM calculations and experiments concerning the surface deformation, the wave height and the velocity fields are presented.

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NOTES

Three-dimensional wavenumber-frequency spectrum of wind waves

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Spatial-temporal measurements of wind-generated gravity-capillary waves were made using a scanning laser slope gauge during two recent field programs in coastal environments (High Resolution Remote Sensing Main Experiment in 1993, and Coastal Ocean Processes (CoOP) - Air-Sea Gas Exchange Experiment in 1995). The results of wave slope spectra on clean water show a well-defined correlation with the wind friction velocity. However, our spectral values at higher wavenumbers are significantly higher than previous laboratory results. In the presence of surface films wave spectra may decrease by more than one order of magnitude at lower wind stresses. The dispersion characteristics of short waves vary markedly depending on the wavenumber, the wind stress, and the surface chemical condition. Some results in the presence of surface films at intermediate winds show much higher apparent phase speeds than the theoretical dispersion relation. This may be because of an enhanced near-surface current or because of the relative increase of wave energy that is phase-locked to longer steep gravity waves.

Using a wave wire array, spatial-temporal information of gravity waves was obtained under typical oceanic conditions. Data sets from three field experiments were used in this study: Coastal Ocean Probing Experiment and Marine Boundary Layers - West Coast experiments took place in open ocean conditions while Riso Air-Sea Experiments (RASEX) were conducted in near shore shallow waters. The Maximum Likelihood Method was applied for calculation of the frequency - wavenumber spectra. In order to evaluate the accuracy of the spectral analysis, the method was tested using computer generated waves of different frequencies spread over a range of wavenumbers and directions. It was found that the method produced satisfactory results and could be used to determine the speed and the direction of propagating gravity waves.

The wave fields in the open ocean and under shallow coastal conditions are substantially different. The results of the RASEX experiment shows that at the frequencies of narrow-banded dominant waves and their bound higher harmonics, the wave propagation speed is consistent with that of the dominant waves. At other frequencies the propagation speed is close to the linear dispersion relation. On the other hand, in open ocean conditions the wave speed of shorter gravity waves is consistently much higher than that predicted by the linear theory. This deviation is too large to be attributed to the Doppler shift by surface currents. Our results, therefore, suggest that the frequency spectrum is mostly determined by broad-banded sharp-crested dominant gravity waves and their bound harmonics rather than by superposition of linear waves of different scales.

NOTES

BENJAMIN-FEIR INSTABILITY OF 3D GRAVITY-CAPILLARY WAVES

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The modulational instability of some solutions of the equation

$$\partial_x(\partial_t\eta + \eta\partial_x\eta + s\partial_x^3\eta + \partial_x^5\eta) + \partial_{yy}^2\eta = 0, \quad s = \pm 1 \qquad (*)$$

is considered. This equation generalizes the celebrated Kadomtsev-Petviashvili equation (KP), and it is obtained in [1] for water surface waves due to the presence of certain surface effects. These effects are caused either by surface tension or by an elastic ice-sheet floating on the water surface. Using the centre-manifold reduction of the dynamical system, describing travelling waves, we find wave solutions of $(*)$ which are periodic in the x-axis direction (the direction of wave propagation) and exponentially decay in the y-axis direction. Unlike the case of KP equation, treated in [2], there are solutions of this type bifurcating from the quiescent state also for $s = 1$, when the Weber number is less than $1/3$ or initial tension in the ice-sheet is not large. These solutions take place if the length L of the x-periodic wave is less than $2\sqrt{5}\pi$.

The periodic wave solutions of the "embeded" in $(*)$ Kawahara equation

$$\partial_t\eta + \eta\partial_x\eta + s\partial_x^3\eta + \partial_x^5\eta = 0$$

for $s = 1$ are modulationally unstable in the vicinity of the wave number $\kappa_0 = 1/\sqrt{2}$ (which corresponds to the wave length $L_0 = 2\sqrt{2}\pi < 2\sqrt{5}\pi$). We show that this instability is also preserved in the case under consideration of dependant on y waves. Consequently, the equation $(*)$ admits the solutions which are localized in the both spatial directions.

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NOTES

Gravity and capillary-gravity waves for two superposed fluid layers, one being of infinite depth

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We consider two superposed layers of perfect fluids (potential flow), the upper and lighter one being of finite thickness, and the bottom one being of infinite depth. We consider the three following 2-dimensional problems:

Problem 1: gravity waves, with only two parameters: Froude number and density ratio;

Problem 2: capillary-gravity waves, with surface tension acting on the upper free surface. This adds a third parameter, the free surface Weber number;

Problem 3: capillary-gravity waves, with interfacial tension, as well leads to a fourth parameter.

Assuming infinite depth for the bottom layer is physically realistic for many applications, but this leads to major mathematical difficulties. The idea is to treat the problem the same way as finite depth problems: a dynamical system approach is used. After several transformations (in the frame moving with the waves), the problem can be put into the following (*reversible*) form:

$$\frac{dU}{dx} = L_\mu U + N(\mu, U) \tag{5}$$

where $U = 0$ represents the rest state (flat free surface and interface), x is the unbounded coordinate in the horizontal direction, μ represents the set of parameters, and $L_\mu U$ is the linear part. We only study solutions of (1) near 0. In all the problems we consider, the spectrum of L_μ contains a small number of non zero eigenvalues *near or on the imaginary axis* (2 to 8) and contains the entire real axis (*essential spectrum*), with no eigenvalue in it, except at 0 for problems 1 and 2, due to one of the Bernoulli first integrals which has to be differentiated to be included into (1). Note that in problems 2 and 3, it is possible to have more than four eigenvalues along the imaginary axis. A consequence of the above structure of the spectrum is that one cannot apply a *Center Manifold reduction*, to obtain a small dimensional ODE. In addition, it is necessary in this study to "extract" the eigenvalue 0 from the continuous spectrum which crosses the imaginary axis (for Pbs 1 and 2).

Using an adapted *Lyapunov-Schmidt technique* we prove existence and compute *periodic travelling waves* for Pbs 1,2,3. In addition, for Pbs 2 and 3, for values of the parameters near a critical surface where group and phase velocities are equal (two double eigenvalues of L_μ along the imaginary axis), we use a *normal form reduction in infinite dimensions* and a Fourier transform analysis to prove existence and compute

solitary waves with damped oscillations at infinity. The fact that the spectrum of L_μ crosses the imaginary axis implies in particular that the solitary waves have a *polynomial, instead of exponential, decay at infinity.*

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SHORT-CRESTED WAVES: A THEORETICAL AND EXPERIMENTAL INVESTIGATION

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Short-crested waves are the genus patterns among three-dimensional waves, due to the interaction of two progressive plane waves propagating in two arbitrary directions. Their two-dimensional limits are the progressive waves (same direction of propagation for both plane waves) and the standing waves (the two plane-waves propagate in two opposite directions). These two limits define a range where short-crested wave fields lie. The present work is an analytical and experimental study of symmetric short-crested waves.

In order to describe the evolution of the wave field, we solved the complete equations using a perturbation method. This method allowed us to calculate an analytical solution for the complete problem of capillary-gravity short-crested waves in water of finite depth up to the sixth order.

Then, experiments were conducted in the IRPHE wave tank facility for different amplitudes, angles and wavelength in the range of capillary-gravity waves. An optical tool, allowing to measure the two-dimensional slope over a square area, was deviced. A new integration method was also developped to provide the surface shape over the same area. The infered surface shape showed good agreement with the analytical results. The use of the bi-orthogonal decomposition signal processing method provided the periodic and progressive properties of these three-dimensional waves.

NOTES

Spectral characteristics of short wind waves

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The dynamics of short wind waves plays an important role in small-scale air-sea interaction processes and radar backscatter from the sea surface. To advance the knowledge in this area, a comprehensive study of 2-D wave number spectra with regard to the wind speed dependence, spectral shape, and angular dispersion has been performed. The 2-D wave number spectra were obtained from measurements of the water surface slope with a refraction-based optical technique. The measurements comprise data from laboratory wind/wave facilities at the IMST (Marseille, France), Delft Hydraulics (Delft, The Netherlands), the Institute for Environmental Physics (Heidelberg, Germany), the NASA Air-Sea Interaction Facility at Wallops Flight Facility (Wallops Island, VA), and field data obtained during the MBL ARI West Coast Experiment in 1995.

Directional wave number spectra of short wind waves are presented for a wide range of experimental conditions - fetches of 5 m to infinite and wind speeds from 2 m/s to 15 m/s. The omnidirectional saturation spectra show a consistent equilibrium range that extents well into the capillary wave region until a sharp cutoff occurs around 1100 rad/m. The fact that this cutoff is almost wind speed-independent implies that viscous damping is not the dominant dissipation mechanism for capillary waves. In order to assess the relative importance of the viscous dissipation, the total viscous dissipation determined from the spectra is compared to the energy input by the wind. The comparison of the spectra from the lab and the field show large scatter of the spectral densities at low wind speeds. This can be attributed to the effects of surface films and background wave conditions. For higher wind speeds the dependence of the spectral density on the friction velocity is found to vary with the wave number from u_* for short gravity waves to almost u_*^3 for capillary waves.

In the field the spectral densities at low wind speeds are higher when compared to laboratory data at long fetches ($> 50\,\mathrm{m}$). However, the short fetch lab data show an overshoot in the spectral density for capillary waves that could also play a role under varying wind conditions in the field.

NOTES

BREAKING WAVES, LOCAL SINGULARITIES AND DROPLET STATISTICS

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Simple well controlled laboratory experiments can show a host of wave breaking phenomena. These include self-focusing singularities and critical slowing near threshold. We experimentally explore what types of liquid surface singularities are possible and analyze their local structure. Parametrically forced standing waves (Faraday waves) may break leading to a local power-law divergence on the free surface. Droplet ejection and air entrainment are also observed in these tabletop experiments. We have analyzed the threshold and statistics for these turbulent breaking capillary waves.

NOTES

THREE-DIMENSIONAL WAVE-WAVE INTERACTIONS IN BOTH SHALLOW AND DEEP WATER

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Based on small perturbation theory and up to 5-wave interactions, Lin and Perrie (1997) obtained three-dimensional wave-wave interactions in shallow water when the normalized wave steepness ($ak\frac{3+\tanh^2 kh}{4\tanh^3 kh}$) exceeded than 0.3, where a, k, and h are wave amplitude, wave number, and water depth, which agrees well with McLean's instability analysis (1982).

In deep water, the 4-wave interactions (two-dimensional wave-wave interactions) are about two-orders of magnitude greater than those for 5-wave interactions. However, Su (1982) has observed three-dimensional wave-wave interactions in his deep water experimental data. Su and Green (1984) suggested that coupled 4- and 5-wave interactions can trigger three-dimensional instabilities ($ak \geq 0.3$). Numerical simulations by Lin and Su (1998) showed that three dimensional wave-wave interactions (5-wave interactions) dominate when the 4-wave and 5-wave interactions couple, not because of the wave steepness, but rather due to the narrow spectral width.

The three-dimensional wave-wave interactions are finite amplitude wave-wave interactions. Previous small perturbative methods are not suitable to study these finite amplitude wave-wave interactions qualitatively or quantitatively. The first results from our new global Pseudospectral method to study these finite amplitude wave-wave interactions qualitatively and quantitatively seem encouraging (Lin and Kuang, 1998).

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NOTES

FLEXURAL-GRAVITY WAVES: STABILITY, RESONANCE GENERATION, EDGE PHENOMENA.

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The wave phenomena in the system ideal fluid beneath an elastic sheet are considered. The stability of a periodical flexural-gravity wave is investigated with respect to small- amplitude waves (noise harmonics) with arbitrarily oriented wave vectors. It is demonstrated that, if the unperturbated wave number is greater than some critical value, then the instability related to three-wave interactions between the unperturbed wave and noise enhances certain noise harmonics and lowers the main wave amplitude. In the opposite case, one deals with the Benjamin-Feir instability which leads to the decoy of the main wave envelope into solitons. In dependence on fluid depth and wave vector the fronts of the solitons are parallel to the wave vector or make up nonzero angle with it.

The spectral properties of the flexural-gravity waves, propagating in the ideal fluid beneath an elastic ice sheet with rectilinear nonhomogeneity are investigated. The nonhomogeneity can simulate a crack, an ice ridge or an ice channel. The dispersion curves related to the edge waves are constructed. The edge waves propagate along the nonhomogeneity , and its energy is localized in a vicinity of the nonhomogeneity. The resonance generation of the edge wave is occured under the influence of external pressure field, moving along the nonhomogeneity with the group velocity of the wave and oscillating with the wave frequency in the moving reference frame. It is estimated the critical velocities of the pressure field motion needed for the resonance generation of the waves in an ice channel.

NOTES

On the role of nonlinear energy transfer in the evolution of wind wave spectra

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The explicit calculation of nonlinear energy transfer (NLET) is a key element of the wave-forecasting model of the next generation. The purpose here is to develop a few methods to calculate NLET precisely and efficiently and to investigate the role of NLET in the evolution of wind-wave spectra.

First, the RIAM method and its simplifed scheme, the SRIAM method, were developed for deep water waves. The performance of the RIAM and SRIAM scheme and the evolution of wind-wave spectra based on the schemes were examined in comparison with other methods, especially the WAM method. The numbers of resonance configurations dealt with are 1, 20, and about 2000 for the WAM, SRIAM, and RIAM method, respectively; the SRIAM method is available for operational use. The RIAM and SRIAM methods proved to have the same level of accuracy as that of rigorous methods. In consequence they are free from a few sorts of unrealstic evolution the WAM method has.

Then, the evolution of wind-wave spectra due to NLET only was examined with the other source terms omitted. Starting from various initial conditions, the spectra examined approached a universal spectral form of frequency to -4, evidence that NLET controls the self-similar evolution of wave spectra.

Next, the evolution based on the wave model with NLET and other conventional source terms included was compared with the evolution of wind-wave spectra in a wind flume. Some inconsistency was found between the model and the laboratory experiment, suggesting the necessity of our further understanding of dissipation terms and others.

Finally, the RIAM method for deep water waves was extended to that for waves in moderate finite depth. Though a simple extension was numerically unstable, an improved scheme yielded smooth NLET.

NOTES

Nonlinear evolution of a step initial condition in the Benjamin-Ono equation

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The solution of the Benjamin-Ono equation is presented for a step initial condition. This models the evolution of an internal bore wave in deep fluids. The Whitham modulation theory is used to construct the asymptotic solution which provides an accurate description of the wave evolution in the small dispersion limit. It is shown that the initial step profile evolves into a train of solitary waves and the total number of created solitary waves increases without limit in proportion to time. The amplitude of the leading solitary wave is then found to be four times the amplitude of the initial step.

NOTES

THE INITIAL GENERATION OF WIND WAVES AND LANGMUIR CIRCULATIONS

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Long streaks, or windrows are often observed at wind-driven water surfaces, and are believed to be the surface manifestation of subsurface longitudinal vortices which, along with wave breaking, may be responsible for much of the vertical transport in the surface layers of the oceans, lakes and other water bodies. This phenomenon owes its name to Irving Langmuir (1938), who observed that surface streaks were associated with longitudinal counterrotating vortices roughly aligned with the wind.

We present laboratory measurements of the generation and evolution of Langmuir circulations as an instability of a wind-driven surface shear layer. The shear layer, which is generated by an accelerating wind starting from rest above a quiescent water surface, both accelerates and deepens monotonically until the inception of the Langmuir circulations. The Langmuir circulations closely follow the initial growth of the wind waves and rapidly lead to vertical mixing of the horizontal momentum and a deceleration of the surface layer. Prior to the appearance of the Langmuir circulations, the depth of the shear layer scales with $(\nu t)^{1/2}$ (ν is the kinematic viscosity and t is time), in accordance with molecular rather than turbulent transport. For final wind speeds in the range 3 to 5 m/s, the wavenumber of the observed most unstable Langmuir circulation normalized by the surface wavenumber , k^*_{lc}, is 0.68 ± 0.24, at a reciprocal Langmuir number, La^{-1}, of 52 ± 21; although the reciprocal Langmuir number rapidly increases prior to the appearance of the streaks. One of the primary conclusions of this work is that the time scales for the initial generation of wind waves and Langmuir circulations are comparable, and that the flow can not be simply characterized by a single Langmuir number as has been done in most theoretical models. The observations are compared with available theoretical results, although none are directly applicable to the conditions of the experiments. The implications of this work for the generation and evolution of Langmuir circulations in the ocean and other natural water bodies are discussed.

A full account of this work will be published in the *Journal of Fluid Mechanics* by Melville, Shear & Veron (1998).

NOTES

Wave Interactions in the Equatorial Waveguide

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The equatorial waveguide supports a wide variety of wave modes: Poincare (gravity) , Rossby (planetary), Yanai (planetary-gravity) and Kelvin. The nonlinear interaction of these waves is particularly interesting since it couples dispersive waves to a nondispersive wave (the Kelvin wave). The interactions are through triad resonances (localized in Fourier space) and result in nonlocal, nonlinear terms in the equation for the profile of the Kelvin wave. Important questions are whether such interactions can prevent the Kelvin wave from breaking, and whether a finite amplitude traveling state emerges from the interaction. Exact solutions for simple configurations can be found, and more general configurations are studied with a spectral shallow water code for the Equatorial waveguide. Interactions catalysed by external forcing (such as land-sea contrast) are also discussed.

NOTES

On the interaction among wind, wind waves and swell

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Wind, wind waves and swell interact in a complicated way. As usually expected the effects of swell to various sea surface phenomena is negligible unless the swell steepness is large. However, with an increase in swell steepness, swell shows complicated effects on see surface phenomena, and the effects critically depend on the propagation direction of the swell relative to the wind direction. The changes of wind waves and surface drift current by steep swell were discussed previously (Mitsuyasu 1997). Here we discuss the change of wind field over sea surface by swell coexisting with wind waves. It is shown that the swell propagating against the wind simply increases sea surface roughness with an increase in swell steepness, while the swell propagating in the direction of the wind shows a bit complicated effect on the sea surface roughness. That is, in the latter case, swell of small steepness shows little effect on the sea surface roughness, swell of moderate steepness decreases the sea surface roughness and swell of large steepness increases the sea surface roughness. Such a complicated change of sea surface roughness by swell will be discussed in association with the change in wave field.

NOTES

Experimental investigation of the turbulent wake generated beneath a 3D breaker

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The turbulence and surface drift introduced by wave breaking contribute to near-surface circulation and to the exchange of momentum across the air-water interface. Because ocean wave evolution is influenced by wave field directionality, it is important to understand how directionality influences breaking dynamics. This study was designed to explore the impact of wave directionality, specifically spatial focusing and resulting short-crestedness, on breaking-induced turbulence and surface drift. The study was conducted in a 4 m x 11 m test section of the Gunther Family Wave Basin at the Massachusetts Institute of Technology. An isolated, short-crested breaking event was generated using a combination of frequency and spatial focusing created through the action of thirteen wave paddles. For comparison a wave of uniform crest (two-dimensional) was also generated using frequency focusing alone. The three-dimensional velocity field was measured using an array of acoustic Doppler probes (ADV). Surface displacement was measured using an array of resistance-type wave gages. The excellent repeatability of the wave generation technique allowed us to estimate velocity statistics using ensemble averaging of multiple events. To complement the spatial mapping of velocity, flow visualization was used to delineate the spatial extent of the turbulent wake.

The magnitude of turbulent velocities measured for the two and three dimensional breakers were comparable, although the short-crested breaker produced greater vertical penetration. Beneath the two-dimensional breaker wake turbulence values reach 0.02C near the surface, where C is the characteristic phase speed, and penetrated three wave heights. At the centerline beneath the three-dimensional breaker turbulent velocities are also 0.02C at the surface, but penetrate to a depth of four wave heights.

An initial drift velocity of 0.03C generated beneath the two-dimensional breaker decayed as $t^{-0.5}$, consistent with previous two-dimensional experiments and theoretical prediction. A three-dimensional breaker of comparable breaking height also generated an initial surface drift of 0.03C at the center, but a drift of only and 0.01C at one-third of the crest length. The surface drift decayed more rapidly at the centerline, $t^{-1.3}$, than off-center where t^{-1}, and in both locations decayed more rapidly than the two-dimensional case. The short-crested breaker also generated strong vorticity not observed for the uniform crest.

NOTES

THE INTERACTIONS OF SWELL, WAVES AND SEA SURFACE ROUGHNESS

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Most recent experiments treat the drag coefficient C_d as a scalar, with friction velocity, U_*, in the same direction as the wind velocity, U_{10}. Smith et al (1992) and Donelan et al (1993), in analysis of data from the North Sea and Lake Ontario, suggested that the sea surface is rough for young waves and becomes relatively smooth as waves become more mature. Their analysis is based on selected data, where swell was *absent.* Since that time, Dobson et al (1994) measured wind stress and wave parameters on the Grand Banks of Newfoundland. However, they were unable to confirm the HEXOS and Lake Ontario results. Because swell is always present on the Grand Banks, it is impossible to select data which has only wave spectra. In their analysis, Dobson et al (1994) neglect low frequency spectral peaks, regarding these peaks as swell when their mean directions are *not* in the wind direction. The results that Dobson et al (1994) were able to obtain are very noisy.

However, for ocean waves, forced by a given wind direction, Reider, Smith and Weller (JGR: 1994) have suggested that the wind stress direction is *not* in the wind direction, but lies between the wind direction and the dominant wave direction. Thus the friction velocity, U_*, and the wind velocity, U_{10}, may not be in the same directions, implying that the drag coefficient C_d is *not* simply a scalar.

The presence of swell complicates estimates of C_d. Donelan, Drennan and Katsaros (JPO: 1997) suggest that swell may strongly influence C_d. Taken by itself, swell is smooth. However, swell does interact with wind-generated waves, through the 4-wave interaction mechanism, in deep water. Thus, indirectly, swell can have a large impact on the spectral energy balance which defines how waves evolve and mature. Implicitly, swell can therefore have an impact on C_d, which defines the sea surface roughness between waves and the wind.

In this study, we use the kinetic equation for spectral wave growth and evolution, following Zakharov (1991). We assume general functional forms for wind input and dissipation, following Perrie and Lin (1997), involving spectral energy, frequency and the air-water drag coefficient. Our formulation for nonlinear wave-wave interactions follows Resio and Perrie (1991), as motivated by Webb (1978). Inverting this kinetic equation leads to estimates for C_d as a function of frequency and angle, using an iterative numerical approach.

We have considered the standard case of growing evolving waves, forced by wind, as

well as situations where swell and waves interaction through 4-wave interactions. We show:

(1) There is a frequency - angle distribution for C_d which evolves in time as the waves evolve and mature. For example, the maximal values for C_d can occur at directions significantly different from the wind direction, depending on the wave age. Integrating these C_d distributions we can define a mean C_d, which we denote $\overline{C_d}$.

(2) $\overline{C_d}$ has high values for young waves, as compared to low values for old waves, which are consistent with the estimates of Smith et al (1992) and Donelan et al (1993).

(3) Swell changes the nonlinear wave - wave interactions, especially when the swell propagates in directions different from the waves. We show that swell - wave interactions also cause substantial modification of the C_d distributions and the concomitant mean variables, $\overline{C_d}$, as suggested by the measurements of Dobson et al (1994).

ORTHOGONAL EXPANSIONS AND NORMAL FORMS FOR WATER WAVES

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A new approach to nonlinear perturbation problems is applied to the Hamiltonian system of irrotational gravity waves. The method addresses resonant interactions with general small-amplitude initial data and is not based on the Fourier transform. It is a Galerkin projection onto an orthonormal set of expansion functions and yields a discrete Hamiltonian with countably infinite degrees of freedom. These expansion functions are spatially localized, and in a sense they provide a more natural description of weakly nonlinear resonance than a Fourier approach. However, the results can be interpreted as a *local* Fourier analysis. This approach can be used in place of traditional Fourier methods, making calculations more tractable in the cases of slowly varying depth and resonant interactions in large domains. Resonance criteria are simple and intuitive based on sum rules of local frequencies. Moreover, deep water and shallow water limits are included within a unified framework. Computational methods based on this approach will also be discussed.

NOTES

Spatial Variation of Atmospheric Fluxes and Microwave Backscatter Over the Ocean

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Simultaneous and coincident measurements of microwave backscatter at 14 GHz and atmospheric fluxes of heat, momentum, and moisture have been made from an airship over the Pacific Ocean. The mobility of the airship allowed the measurements to be made over an area of approximately 50 by 50 km during several different experimental periods. The area of the experiment, off the coast of Oregon, exhibits many surface features due, for example, to internal waves and sea surface temperature fronts. At wind speeds above 4 to 6 m/s, these surface inhomogenieties had little effect on either the atmospheric fluxes or the microwave backscatter. At lower wind speeds, their effects could be observed in both sets of measurements but many variations of backscatter and fluxes also occurred in the region which were difficult to relate to surface features.

Atmospheric conditions during the experiments were often stably stratified and during these periods, correction of the measured wind speed to an equivalent neutral wind speed using standard techniques failed to remove the stratification dependence of either the backscatter cross sections or the drag coefficients. Since friction velocities and cross sections varied in the same manner in the high-wind speed regime, the reduced friction velocities produced by stable stratification at a given measured wind speed were always accompanied by reduced cross sections. Thus stable stratification reduces the surface roughness as well as the momentum flux and this effect can qualitatively explain the failure of the standard correction to neutral wind speed.

At lower wind speeds, this connection between microwave cross section and friction velocity is broken and the cross section was found to decrease dramatically at very low wind speeds while the friction velocity remained approximately constant. The result was that many restricted regions of the experimental area exhibited simultaneously very low wind speeds, very low microwave cross sections, and very high drag coefficients. These regions on occasion remained relatively constant for periods of hours. The observed reduction in the cross section at very low wind speeds was consistent in its rate of decrease with that predicted by Donelan and Pierson [JGR, 92(C5) 1987] due to viscous effects. The decline seemed to occur at lower wind speeds than predicted, however. The observed increase in the drag coefficients at low wind speeds agreed with those reported recently by Mahrt et.al. [JGR, 101(C6) 1996] and was larger than expected due to viscous effects. We suggest that the failure of the friction velocity to decrease to zero with wind speed may be due to effects of surface waves longer than 50 cm in supporting momentum flux from the atmosphere.

NOTES

THREE-WAVE QUASI KINETIC APPROXIMATION FOR NONLINEAR GRAVITY WAVES SPECTRUM IN FINITE DEPTH WATER

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The generalized kinetic equation is proposed, describing non- resonant three-wave non-linear interactions for the random surfa- ce gravity waves in finite depth water. The modification of tra- ditional kinetic equation is made by means of refusing of tran- sition to the limit of infinite time in an exact solution for the third statistical moments. It permits to take into account a con- tribution of non-resonant three-wave processes and to find the evolution equation owing to an introduction of non-linear attenu- ation of wave component b(k). As a result, the final collision integral contains a smoothed d-function for three frequencies in- stead of an exact one. The parameter of smoothing is defined by a non-linear wave attenuation decrement b(k) governed by a special equation. The system of equations for a rate of wave spectrum evolution and a wave attenuation decrement is named as a quasi kinetic approximation. A preliminary analysis of these equations is fulfilled. It is shown that nearly resonant three-wave interactions can give rise of superharmonics in a spectral shape of wind waves. An intensity of the former depends on the value of parameter kD. The smaller kD the greater intensity of superharmonics. For kD ¿ 1 an effect of non-resonant interactions becomes negligibly small. A spectral shape evolution is very close to one observed experimen- tally by Eldeberky and Battjes(1997) in shallow water laboratory tank. The conclusion is drawn that non-resonant three-wave inter- actions are the very important evolution mechanism in the case of shallow water.

NOTES

NUMERICAL SIMULATION OF CAPILLARY WAVES

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Numerical simulation of dynamical equations for capillary waves excited by long-scale pumping shows the presence of both Kolmogorov spectrum at high wave numbers (predicted by weak-turbulent theory) and non-monotonic spectrum at low wavenumbers.

The value of Kolmogorov constant measured from numerical experiment happens, however, to be different from theoretically predicted one.

We explain the difference by coexistence of "weak" turbulence at high wavenumbers and "frozen" turbulence due to sparcity of the Fourier modes.

Observed results are believed to be general for different physical dispersive systems limited in real space and are confirmed by laboratory experiments.

NOTES

Nonlinear interaction of inhomogeneous wave-fields on deep water

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The Zakharov equation as well as Hasselmann's Boltzmann integral have originally been derived for homogeneous wave-fields. This means that the Fourier-components represent the entire plane. However, most wave-fields are inhomogeneous, and the Fourier-components in practice are determined for, and thus represent, only a limited region of the plane.

In this presentation three different versions of the Zakharov equation are presented. The equations have been derived for infinitely deep water by introducing multiple spatial scales, and by applying the Fourier transform on the fast spatial scale only, roughly corresponding to applying the Fourier transform to a limited region of the plane. Firstly, the derivation including spatial variations in two slow scales leads to an evolution equation, which we named the "Zakharov-Schrödinger equation", as it bears similarities to the Zakharov equation as well as to the cubic Schrödinger equation. Secondly the derivation including spatial variation on just one slow scale leads to an evolution equation, which we named the "inhomogeneous Zakharov equation"; and as expected the derivation taking into account spatial variation on no slow scales leads to the original Zakharov equation.

By manipulating a Stokes wave train we determine relative resolutions of the amplitude spectrum, corresponding to areas with typical length-scale to wave-length ratios on which the Fourier transform has been applied, and for which the different versions of the Zakharov equation are appropriate choices. We found that the original Zakharov equation, the "inhomogeneous Zakharov equation", and the "Zakharov-Schrödinger equation are valid when the relative resolution of the spectrum is of order $O(\epsilon^{\infty})$, $O(\epsilon^2)$, and $O(\epsilon)$. This corresponds to spectra that have been based on areas with typical extend to wave-length ratios of order $O(\epsilon^{-\infty})$, $O(\epsilon^{-2})$, and $O(\epsilon^{-1})$, respectively. ϵ is a small parameter of the problem, i.e. a typical wave-steepness.

It is well known that the Zakharov equation can be used as basis for deriving Hasselmann's Boltzmann integral; thus we examined whether the new versions of the Zakharov equation could also be recasted into stochastic evolution equations. We found it impossible to derive a stochastic evolution equation from the "Zakharov-Schrödinger equation", but the "inhomogeneous Zakharov equation" was recasted into a stochastic evolution equation which is a special case of the well known WAM-model. This derivation, however, provided us the required action density spectrum resolution, and indicates that the action density spectrum should be based on an area with typical extend to wave-length ratio of $O(\epsilon^{-2})$.

NOTES

WIND STRESS AND WAVE DIRECTIONS: AN EXPERIMENTAL STUDY

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A common assumption made in air-sea interactions is that the atmospheric surface-layer wind and stress vectors are co-linear. The drag coefficient parameterisation of the stress assumes alignment of the vectors. However recent open field measurements have shown that, on occasion, stress vector and mean wind vectors are misaligned.

Different explanations have been given. Some authors argued that this misalignment is due to thermal stratification in the airflow since others claimed that directional features of waves could explain this departure.

The main purpose of this work was to study, in neutral stratification conditions, the effect of waves propagating at different angle with regard to the mean wind direction upon the structure of the turbulent boundary layer and more precisely upon the deviation of the stress vector given as follows: $\theta = \arctan(\langle v'w' \rangle)/\langle u'w' \rangle)$, (where u', v' and w' are the fluctuating longitudinal, lateral and vertical velocities).

A series of experiments was conducted in the Large IRPHE Wind Wave Tank. They consisted in disturbing a pure wind wave field by an oblique wave.

A complete and a sophisticated experimental set up has been used. It consisted in a triple hot wire to measure the instantaneous fluctuating longitudinal, vertical and lateral wind velocities, an arrangement of capacitive wave probes to determine the wind wave directional spectrum and a laser wave slope gauge associated with an air pressure fluctuation probe to measure along wind and cross wind wave slopes and the two directional contribution to form drag.

Different angles between wind and oblique waves, oblique wave steepness and wind velocities have been considered.

Results show that an oblique wave induces a strong effect upon wind stress (magnitude and direction) and the structure of the boundarylayer. This effect depends on every one of these parameters and the ratio between pure wind wave energy and oblique wave energy.

NOTES

On the Benney-Roskes system

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The Benney-Roskes system has been introduced to model the evolution of a packet of surface waves on sufficiently deep water.

It was later shown by Zakharov and Rubenchik to describe the interaction of high-frequency waves of any nature with waves of acoustic type.

In appropriate limits, it reduces to the Davey-Stewartson or the Zakharov systems.

This lecture, whcih summarizes a joint work with G. Ponce, will address the first rigorous theory of well-posedness of the Cauchy problem for the Benney-Roskes system.

NOTES

Solution of the initial-value problem for the Kadomtsev-Petviashvili equation with quaisperiodic initial data

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The Kadomtsev-Petviashvili (KP) equation is an approximate model for waves of moderate amplitude, propagating in shallow water of uniform depth. Krichever (1976) showed how to construct a huge family of exact periodic or quasiperiodic solutions of the KP equation, expressed in terms of Riemann theta functions. These solutions depend on the remarkable connection between this equation and the theory of Riemann surfaces. Krichever's procedure starts with an arbitrary compact, connected Riemann surface of genus g, and constructs from it a g-phase, quasiperiodic solution of the KP equation.

The work presented here can be viewed as the inverse of Krichever's procedure. We start with appropriate initial data for the KP equation (a g-phase, quasiperiodic solution of the KP equation at $t = 0$), and construct from these data the ingredients needed for Krichever's procedure: a Riemann surface, plus a set of points (a divisor) on that surface. The construction is completely explicit. When combined with Krichever's earlier work, this solves the initial-value problem for the KP equation, at least for this class of initial data.

This work was done jointly with Bernard Deconinck.

NOTES

3D Dynamics of nonlinear water waves on moderately weak shear currents: wave groups and Langmuir's circulations

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The present study of nonlinear interactions among wind waves propagating on the wind driven drift current is aimed at the unresolved problems of formation of the wave groups and mechanisms of the waves transverse variability. A simple model describing the *coupled* dynamics of narrow-banded wave packets and wave induced Langmuir circulations has been derived.

The mean drift current is presumed to be unidirectional, horizontally uniform and $O(\mu)$ weak compared to the characteristic phase velocity of the water waves, where $1 \gg \mu \gg O(\epsilon^2)$ and ϵ is the waves' nonlinearity parameter. We shall refer to this situation, typical of the so called "young waves", as that of *moderately weak*current. Note, that commonly the Craik-Leibovich scaling $\mu = O(\epsilon^2)$ is employed, which is more appropriate for "old waves". Description of evolution of narrow-band wave packets of weakly nonlinear surface waves is sought by means of an asymptotic expansion based on the smallness of both ϵ and μ. At the leading order the wave field is described in terms of slowly varying envelope amplitudes $A(\epsilon_x x, \epsilon_y y, \epsilon_t t)e^{i\Theta} + c.c.$ (The Cartesian frame is employed with $x-$coordinate directed downstream.) The waves generate low frequency vortical perturbations to the mean current interpreted as Langmuir circulations, (*not necessarily regular and well developed).* We look for the self-consistent weakly nonlinear regimes of the packet dynamics, where nonlinearity due to interaction with the induced motions is balanced by dispersion at the leading order, while the induced motions remain weakly nonlinear and the contribution due to the standard cubic Schrödinger type interaction is negligible. A number of different scenarios of the wave transverse instability is found possible, depending on the anysotropy parameter (ϵ_y/ϵ_x). In particular, the most relevant strongly anysotropic regime $(\epsilon_x \ll \epsilon_y^2)$ is found to be described by the system presented here in normalized variables

$$iA_t + A_{yy} + AQ = 0\,, \quad \partial^2_{tt} Q = s\partial^2_{yy}(\mid A\mid^2); \tag{6}$$

where Q is the x velocity component of the induced vortical perturbations, the only coefficient $s = \pm 1$ being specified by the direction of wave propagation (upstream/downstream) and the vertical profile of the current. The system predicts strong transverse instability of the plane waves resulting, for a certain range of parameters, in formation of self-induced wave-guides, similar to those common in nonlinear optics and plasmas. A generalization of the model for the case of wide spectrum in k_x has been also carried out. The results have numerous implications, partly discussed in the present work.

NOTES

Three-dimensional surface waves propagating over long internal waves

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A current, such as may be generated by long internal waves, interacts with short surface waves and the resultant patterns on the sea surface are of interest. In particular, regions of steep breaking waves may be relevant to specular radar scattering.

A simple approach to modelling this problem is to take a set of short, surface waves of uniform wavenumber on the sea surface, as may be caused by a gust of wind. The direction of propagation of the surface waves is firstly taken to be the same as that of the current, and surface tension and viscous effects are neglected. We have a number of methods of solution at our disposal: linear (one-dimensional) ray theory is simple to apply to the problem, a nonlinear Schroedinger equation modified to include to effect of the current can be derived and solutions can be found using a fully nonlinear potential solver. Comparisons between the 'exact' nonlinear calculations (which are too complicated/ computationally intensive to be extended to three dimensions) compare well with the two approximate methods of solution, both of which can be extended, within their limitations, to model the full three-dimensional problem; here we present three-dimensional results from the linear ray theory.

By choosing such a simple (although we consider physically realistic) initial state of uniform wavenumber short waves and assuming a sinusoidal surface current, we can reduce the two-dimensional problem to three non-dimensional parameters: two velocity ratio parameters, θ and γ defined by

$$\theta = \frac{U_c}{V} \qquad \text{and} \qquad \gamma = \frac{c_1}{V} = \left(\frac{g}{k}\right)^{1/2} \frac{1}{V}, \tag{7}$$

where g is acceleration due to gravity, k and c_1 are the initial wavelength and phase speed respectively of the short waves, V is the phase speed of the internal wave and U_c is the maximum magnitude of the surface current. The third parameter is the initial steepness of the short surface waves which is just a simple multiplier for linear theory.

Moving into three-dimensions, we now consider an initial condition with a uniform wavetrain at an angle α say, to the propagating current, thus introducing a fourth parameter into the problem. Extension of the linear ray theory from one space to two space dimensions is numerically quite simple, and the only difficulty lies with the presentation of results, due to the large number of variables now present in the problem such as initial wavenumber, angle of propagation, position in (x, y, t) space etc. We give particular attention to waves which are strongly refracted and focus in space-time. Interesting preliminary observations include the formation of two distinct foci for some values of α. Also, we find a collimation of the short waves with the direction of the propagating current.

NOTES

3D BUBBLE PLUMES BEHIND BREAKING WAVES INSIDE THE SURFZONE

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Observations of bubble plumes with their white capping reveal that, under appropriate conditions, the structure of bubble plumes generated by continuous wave breaking in the surfzone show the 2D formation first, then break into 3D formations, and finally into more or less uniform distribution. A possible physical explanation for the 2D to 3 D evolution will be given, together with some video/photographic evidences. In addition, we shall present some detailed measurements of spatio-temporal distributions of void fration and bubble size spectra due to wave breaking inside surfzones.

NOTES

3D PATTERNS IN WAVE GENERATED CIRCULATION

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When waves break on a beach the breaking process is associated with large gradients in the radiation stresses and the mass fluxes that act as forcing for strong nearshore circulation flows. The analysis of such flows has developed rapidly from the simple analytical solution for uniform longshore currents (Longuet-Higgins and others, 1970) to complex numerical models that utilize the power of modern computers.

This presentation will describe the development of and results from a quasi-3D model for such flows. The model combines a solution to the depth integrated equations in 2 horizontal dimensions with an analytucal solution for the vertical variation of the currents and infragravity wave profiles. It turns out the the vertical structure of the flow gives important contributions to the lateral dispersion of momentum, and hence can change the flow pattern substantially.

The model is a comprehensive nearshore circulation model that solves the hydrodynamical equations in the time domain and that can be used under general topography. Results will be shown for some examples and particular emphasis will be given to beaches with longshore bars. On such beaches the longshore variation of the topography cause disturbances of the flow and both shear waves and rip currents are frequent phenomena. Comparison with laboratory measurements shows good agreement for a particular example, but the model results also reveal the enormous complexity of mechanisms involved and the possible changes in the flow patterns that in some cases can develop with seemingly small changes in parameters.

Thus, with the availability of comprehensive and reliable models for the nearshore circulation we are entering an era where we not only need to verify the correctness of the computational output. One of the major problems is in fact to identify and understand the many flow phenomena that show up in the model output some of which may not have been identified before because of lack of data.

NOTES

Closures for dispersive random waves

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Many systems in Nature receive energy input continuously in some range of scales, and dissipate this energy in scales orders of magnitude away. Often these systems reach a statistically steady state, in which energy "flows" from source to sink through the intermediate scales, denoted inertial range, by mechanisms which are strongly dependent on the nature of the system. This talk will focus on weakly nonlinear dispersive systems -with internal waves in the Ocean as a prototype-, in which resonant interaction among waves is the main mechanism for energy transfer. These systems are known to develop self-similar energy spectra within the inertial range, analogous to the Kolmogorov spectrum of isotropic turbulence. An important example is the universal spectrum of internal waves in the Ocean reported by Garret and Munk. A body of theory exists regarding this kind of "turbulent cascades", under the name of weak turbulence. Despite the success of this theory in a variety of applications, its range of validity has not been fully established.

In joint work with Majda and McLaughlin, a family of one-dimensional nonlinear dispersive wave equations has been introduced as a model for assessing the validity of weak turbulence theory for random waves. These models have an explicitly solvable weak turbulence theory, with Kolmogorov-type wave number spectra exhibiting interesting dependence on the parameters in the equations. These predictions of weak turbulence theory, however, do not agree with the spectra observed in the numerical solutions. Instead, an alternative closure theory is developed, which successfully predicts the observed spectra for all values of the parameters tested.

In this talk, the reasons for the failure of weak turbulence theory in this one-dimensional model will be discussed, with particular emphasis on issues that may extend to the multidimensional case. In particular, it is found that the two standard limits of turbulence theory, namely those of an infinite box size (i.e., a continuous spectrum) and an infinitely long inertial range, do not commute. Thus the mechanism for energy transfer among very short waves is essentially discrete, which changes quite dramatically the nature of the energy spectrum.

NOTES

Detection of Nonlinear Energy Transfer between Ocean Waves by Direct Numerical Simulation – Part I. Methodology and Preliminary Results

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At present, the energy spectrum $\epsilon(\boldsymbol{k})$ of the ocean waves is considered to evolve in space and time according to the energy balance equation:

$$\frac{\partial \epsilon(\boldsymbol{k};\boldsymbol{x},t)}{\partial t} + \boldsymbol{c}_g(\boldsymbol{k}) \cdot \nabla_h \epsilon(\boldsymbol{k};\boldsymbol{x},t). = S_{nl} + S_{in} + S_{dis}. \tag{8}$$

Among the three source terms on the right hand side, we will focus our attention in the present work to S_{nl}, the energy transfer between different wave modes due to nonlinearity. For S_{nl}, Hasselmann (1962) has derived a complicated but explicit expression

$$\begin{aligned} S_{nl}(\boldsymbol{k}_4) &= \iiint |T_{1234}|^2 \delta(\boldsymbol{k}_1 + \boldsymbol{k}_2 - \boldsymbol{k}_3 - \boldsymbol{k}_4)\delta(\omega_1 + \omega_2 - \omega_3 - \omega_4) \\ &\quad \times \{N_1 N_2 (N_3 + N_4) - N_3 N_4 (N_1 + N_2)\}\, d\boldsymbol{k}_1\, d\boldsymbol{k}_2\, d\boldsymbol{k}_3, \end{aligned} \tag{9}$$

where $N(\boldsymbol{k}) = \epsilon(\boldsymbol{k})/\omega(\boldsymbol{k})$, $\omega_i = \omega(\boldsymbol{k}_i)$ $(i = 1,2,3,4)$, T_{1234} is some complicated function of $\boldsymbol{k}_1$, $\boldsymbol{k}_2$, $\boldsymbol{k}_3$, $\boldsymbol{k}_4$, and δ is Dirac's delta function.

This expression for nonlinear energy transfer has been derived under various assumptions, such as random phase approximation, weakness of interactions between different wave modes, discard of all the higher order interactions than those with four-wave processes, and so on. In this work we want to critically assess the validity of Hasselmann's S_{nl} by comparing it with the results of direct numerical simulations based on the deterministic governing equations for nonlinear water waves. In this Part I, we first establish the methodology to achieve this aim, and then present the results of preliminary calculations.

Given an energy spectrum $\epsilon(\boldsymbol{k})$ at $t = 0$, we construct fields of free surface displacement $\eta(\boldsymbol{x})$ and velocity potential $\psi(\boldsymbol{x})$ at the free surface by a superposition of linear free waves in a way to conform to $\epsilon(\boldsymbol{k})$. Then $\eta(\boldsymbol{x})$ and $\psi(\boldsymbol{x})$ are updated according to the governing equations for nonlinear water waves by the "high-order spectral method" of West et al.(1987) until $t = 20T_p$ (T_p is the period corresponding to the peak mode). $\eta(\boldsymbol{x})$ and $\psi(\boldsymbol{x})$ at $t = 20T_p$ are then transformed to $\epsilon(\boldsymbol{k})$ via the "complex amplitude function" $b(\boldsymbol{k})$ of Zakharov (1968). The nonlinear energy transfer function is finally evaluated from the difference between $\epsilon(\boldsymbol{k})$ at $t = 0$ and that at $t = 20T_p$. We've performed several preliminary calculations for JONSWAP and Pierson-Moskowitz spectra so far. Although the quantitative agreement with Hasselmann's S_{nl} is still quite unsatisfactory due to lack of sufficient resolution in $\boldsymbol{k}$ space, nevertheless the transfer function thus obtained can reproduce most of the various important aspects of Hasselmann's S_{nl}.

NOTES

LABORATORY EVIDENCE OF FREQUENCY DOWNSHIFT IN THREE-DIMENSIONAL WAVES IN A WAVE TANK

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The frequency downshift in the evolution of Stokes waves has until recently been considered as a purely two-dimensional phenomenon: A uniform wave train is generated at one end of a long wave tank, the frequency spectrum is measured at various fixed points along the tank, and under certain conditions it is observed that the peak of the spectrum is permanently downshifted at large fetch. A permanent downshift has not been predicted by two-dimensional conservative theories. Several two-dimensional theories enhanced with dissipation do predict a permanent downshift, in qualitative agreement with the experiments.

Three-dimensional evolution was recently considered numerically by Trulsen & Dysthe (1997) using a modified nonlinear Schrvdinger equation. Their two main results are: (1) While conservative two-dimensional evolution of Stokes waves does not appear to predict a permanent downshift, three-dimensional evolution can produce a downshift without dissipation. (2) If the original Stokes wave is long, the peak of the spectrum can be downshifted to a collinear sideband. If the original Stokes wave is sufficiently short in comparison with the width of the tank, the peak of the spectrum can be downshifted to an oblique sideband. The nonlinear evolution of a Stokes wave can hence result in a standing wave across the tank at large fetch.

We here report on experimental results obtained by Stansberg (1993) that include measurements of cross-tank modulation in the evolution of Stokes waves. We find that when the original Stokes wave is sufficiently short in comparison with the width of the tank, the peak of the spectrum can be downshifted to an oblique sideband. When the original Stokes wave is longer, the peak of the spectrum can be downshifted to a collinear sideband. A standing wave across the tank at large fetch is indeed observed. Hence the experimental results support the numerical prediction that three-dimensional cross-tank modulation can play a significant role for the frequency downshift.

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NOTES

Limiting configurations of two- and three-dimensional free-surface flows

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A common feature of nonlinear free-surface flows is that they ultimately reach a limiting configuration as one progresses along branches of solutions. The properties of the limiting configuration depend on which effects are included in the mathematical model. For example, pure gravity waves approach a limiting configuration with a discontinuity in slope at the crest and an enclosed angle of 120°. However different limiting configurations (such as profiles with enclosed bubbles, cusps and other singularities) are obtained when the effects of surface tension, vorticity or the motion in the upper fluid are taken into account. We shall present a global view of these various limiting configurations for both two- and three-dimensional free-surface flows.

NOTES

A LAB TOY MODEL OF AIR–SEA INTERACTION (SURFACE AND INTERNAL WAVES)

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When a liquid absorbs a surfactant of lower density out of the vapor above it, surface waves are generated beyond a certain concentration gradient of the surfactant if this lowers the surface tension of the liquid. It corresponds to a critical value of the Marangoni number for the geometry of Binard convection. Subsequently, those surface waves act like "wind" on the bulk of the liquid which is stably stratified thus leading to internal waves in the liquid layer (Rayleigh–Binard–Marangoni problem or the evolution of a layer subjected to negative buoyancy and surface tension gradients at the open surface). Experimental evidence of such surface and internal waves, for pentane or hexane vapor absorption on liquid toluene, will be provided together with bits of linear and nonlinear theory, and numerics about them. Surface waves may be capillary–gravity (transverse) waves or genuinely surface tension gradient-driven (longitudinal) waves. The nonlinear theory invokes, for instance, in the case of shallow layer conditions, the balance of nonlinearity and dispersion together with an input–output energy balance past an instability threshold.

NOTES

Observations on waveforms of capillary and gravity-capillary waves

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The scattering of microwaves by the sea surface is influenced by Bragg scattering from very short water waves. Capillarity is dominant in waves with wavelengths shorter than 1.7 cm. The ocean surface has waves of a wide range of wavelengths extending from long swells down to ripples with lengths of the order of a millimeter. The roughness of the sea surface to the flow of wind has also a contribution from these very short waves by creating micro-turbulence immediately adjacent to the sea surface. The capillaries can be very steep with great curvature which can generate turbulence at and below the surface. Short surface waves can be generated and modulated by the wind and longer surface waves. Observing the shapes and structures of short wind waves is of vital importance to our understanding of these processes at sea surface.

The two dimensional shapes of short wind waves are found from integrating the surface gradient image data. The images are captured by an optical surface gradient detector (Zhang and Cox 1994). Two sets of data are collected at the different conditions, in a wind wave tank and in the water offshore California. Wave forms and two-dimensional structures of short wind waves are compared. Although the large-scale wind and wave conditions are quite different, the waveforms are resoundingly similar at the small scale. Steep, nonlinear waves in the capillary range featuring sharp troughs and flat crests. The observations also show that most short waves are far less steep than the limiting waveform. Wave forms that resemble capillary-gravity solitons are observed with a close match to the form theoretically predicted for potential flows (Longuet-Higgins 1988,1989, Vanden-Broeck and Dias 1992). Organized capillaries are mainly found as parasitic capillaries on the forward faces of short gravity waves. The maximum wavelength in a parasitic wave train is less than a centimeter. There is a corespondent parasitic peak in the wavenumber slope spectra obtained both from the lab and from the coastal water. The phenomenon of capillary blockage (Phillips 1981) on dispersive freely traveling short waves is observed in the tank but is not evident for waves at sea. The short waves seen at sea propagate in the all the directions while the waves in the tank are much more unidirectional. This is important for the energy exchange among capillaries through weakly wave-wave resonant interactions. A pair of capillary waves propagate in about 80 degrees is a necessary condition for the triad resonant wave interaction. This condition can be satisfied for capillaries at sea and hardly for the capillaries in the tank. The interactions among capillaries at sea could be different from that in a tank.

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